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Achieving A Hydrodynamically Equivalent Burning Plasma in Direct-Drive Laser Fusion

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Focused experimental campaigns, data-driven predictive modeling and advances in diagnostic capabilities have considerably improved the performance of DT-layered implosion experiments on the OMEGA laser, raising the possibility of realizing thermonuclear ignition and energy gains with megajoule-class lasers via direct drive. A key milestone on the path to ignition and high gain is the generation of a burning plasma, where the heating of the plasma must be dominated by the energy provided by the fusion reactions. For the first time in laser direct-drive fusion, we report that experiments on the 30-kJ OMEGA Laser system have demonstrated implosion qualities consistent with a burning plasma when hydrodynamically extrapolated to the 2.15 MJ of energy available at the National Ignition Facility. These hydro-scaled implosions are expected to achieve 86 ± 2% of the Lawson parameter required for ignition and fusion energy output of up to 1.5 ± 0.2 MJ [1]. These improvements in implosion quality on OMEGA were achieved by using a data-driven statistical model [2] to optimize novel Si-doped ablator target designs that increased energy transfer efficiency to achieve the required conditions at moderately high adiabats (α≈5) and high implosion velocities (V_imp > 450 km/s), see Figure 1.

The best performing implosions maximize coupled energy with the use of mid-Z-doped ablators, thinner ice layers, and larger outer radius as compared to previous cyrogenic campaigns at Omega. The new ablator material helps to increase laser energy absorption and mitigates hot-electron preheat of the DT fuel. A large capsule radius reduces the effects of cross-beam-energy-transfer (CBET) and increases the amount of coupled laser energy. New target fabrication techniques were developed to produce and characterize these multi-layer capsules at the larger radii. Additionally, mid-Z dopants in the ablator and a high-adiabat drive help to reduce ablative Rayleigh-Taylor (RT) growth on the shell during the implosion. With reduced RT growth, higher implosion velocities may be achieved by using thinner DT-ice layers, while still maintaining the integrity of the remaining mass. All of these factors play important roles in achieving a hydrodynamically equivalent burning plasma regime in direct-drive laser fusion. Experimental results and scaling calculations will be shown and discussed.

References

[1] V. Gopalaswamy et al., Nature Physics 20 (2024)
[2] V. Gopalaswarmy et al., Nature 565 (2019)

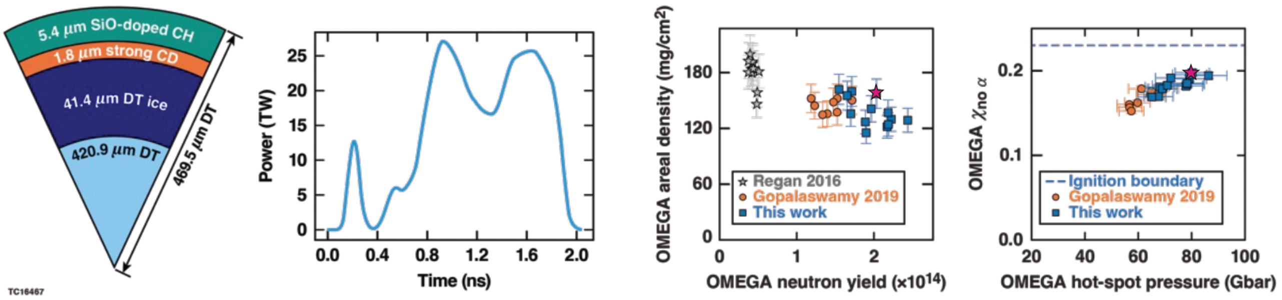

Figure 1: From left to right. (1) Typical target design for experiments that demonstrated hydrodynamic scaling towards a burning plasma. (2) Typical pulse shape for the high-adiabat (α≈5) laser drive. (3) Areal density plotted against neutron yield for a variety of different implosions. (4) The inferred generalized Lawson parameter ($\chi_{no\alpha}$) plotted against hot-spot pressure.